Redesigning BandPass filter

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Executive Summary

Acme company requested 15000 bandpass filters with the specifications of 200kHz center frequency with ±5% tolerance and maximum 50kHz bandwidth. The company provided a schematic for the filter with resistor, inductor, and capacitor with the value of 100Ω, 33uH, and 56nF respectively. For the given circuit, the center frequency was 117.42kHz and the bandwidth was 28.4kHz. The problem is they do not meet Acme company's specification of 190 to 210 kHz of center frequency and 50kHz maximum bandwidth.

The approach was to use TopSpice, which is a computer circuit simulator to produce bode plot for various resistor and capacitor values to measure and compare the center frequencies and bandwidth. Using parametric step function, the team tested the resistor values between 50Ω to 200Ω to obtain bandwidth of 50kHz and capacitor values from 20nF to 100nF for the center frequency of 200kHz. The recommended resistor, capacitor, and inductor values are 160Ω, 20nF, and 33uH. The modified design's recorded center frequency was 197.4kHz and bandwidth of 49.62kHz.

The resistor, capacitors, and inductors were selected from Digi key, which is an online store for electronic parts. They were chosen based on the price for 15000 pieces, tolerance level, quantity in stock, lead time, and shipping cost. The total resistor, capacitor, inductor costs were $161.7, $903.90, $521.73 respectively. Resistor and capacitor had ±5% and the inductor had ±10% tolerance. The lead time was zero and the shipping cost was $21 in total.

In KiCadEDA, which is an electronic design automation software, the printed circuit board (PCB) for the bandpass filter was designed. The dimension for the PCB is 21.59x27.94 mm with one layer of aluminum based material. The total cost to produce 15000 PCB is 450.80 dollars and the arrival time is 7-13 days. The total cost is $2079.29 for 15000 units with an arrival time of two weeks for electronic parts and the board.

Introduction

The Acme filter company has proposed a bandpass filter circuit design to analyze and modify the passive elements based on the given specifications for producing 15000 units. The circuit is designed and simulated in TopSpice, which is an analog and digital circuit simulator for PC [1]. Figure 1 shows the current design in TopSpice. Nodes IN and OUT are used to measure Vin/Vout.

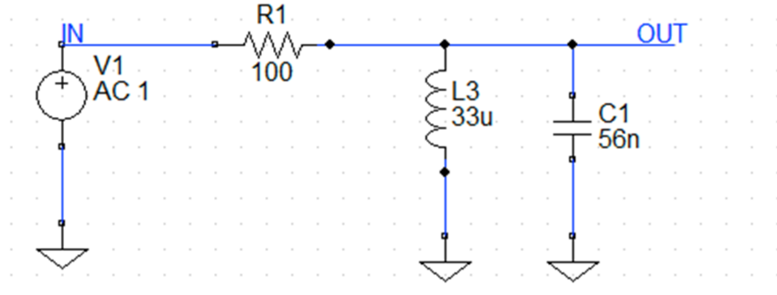

Figure 1: The original band-pass circuit design provided by Acme.

The simulated bode plot for the circuit given by Acme company is shown in Figure 2 with -3dB indicated by crosses.

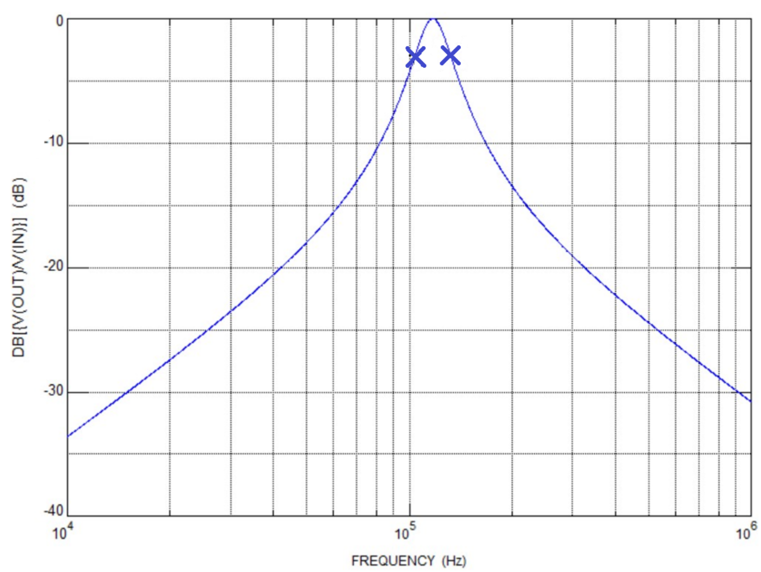

Figure 2: Bode plots for bandpass filter given by Acme

The -3dB bandwidth and the center frequency value of the filter obtained from the plot in Figure 2 is 28.4kHz and 117.042kHz respectively. The required filter specifications given by Acme

Filter company are in Table 1. The process to redesign the bandpass filter is discussed in the experimental methodology section.

Table 1: Filter Specifications [2]

Center Frequency	200kHz	±5%
-3dB Bandwidth	50kHz	Maximum

Background Theory

Bandpass filters are used for filtering continuous analog signals. The basic structure of a bandpass filter includes a resistance and an inductor placed parallel with a capacitor. Equation (1), (2), and (3) are used for calculating the impedance of three components where w represents the angular frequency of the signal. c and l represent the capacitance and inductance of capacitor and inductor, respectively. j is the imaginary number.

$$Z_R = R \tag{1}$$

$$Z_C = \frac{1}{jwc} \tag{2}$$

$$Z_L = jwl \tag{3}$$

When signals pass through a bandpass filter, low frequency signals are blocked by the capacitor and high frequency signals are blocked by the inductor, making only signals with moderate frequencies pass through the relationship between input and output signal of a bandpass filter can be expressed as $\frac{Vout}{Vin}$ or $H(w)$, which is frequently called transfer function or gain. Equation (4) is used for calculating the transfer function.

$$H(w) = \frac{Vout}{Vin} = \frac{Z_C||Z_L}{R+Z_C||Z_L} = \frac{jwl}{R(1-w^2lc)+jwl} \tag{4}$$

The relationship of the gain of a bandpass filter and input frequency can be expressed by a bode plot shown in Figure 3, which is the frequency response of the system for all frequencies.

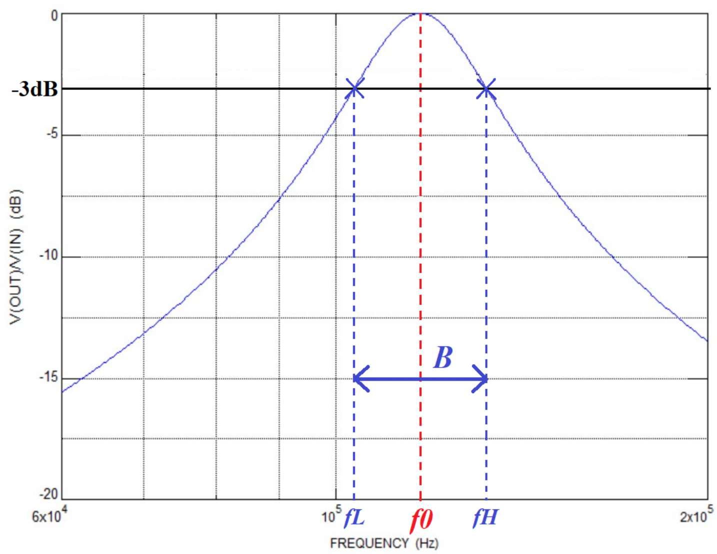

Figure 3: Bandpass filter transfer function graph

The value of gain that is $3dB$ below the maximum value is highlighted. This value is called "half power point" where the output power has dropped to half of its peak value. The two specific frequencies that correspond to the half power point are listed as f_L and f_H above, which represents the cutoff frequency of a bandpass filter. For widely spread frequencies, the term bandwidth is defined, which is the difference between higher cutoff frequency and lower cutoff frequency, as it is shown above as B. Finally, the frequency that corresponds to the maximum value of gain, is defined as center frequency, which can be calculated using Equation (5).

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{5}$$

Experimental Methodology

The specification given by Acme company for 50kHz bandwidth and center frequency 200kHz is not met in the current design with 28kHz bandwidth and 117kHz center frequency. The approach to solve the problem was to use Top Spice to produce bode plots for different resistor and capacitor values and measure bandwidth and center frequency at -3dB discussed in the background section. The simulation types utilized were AC sweep, which performs AC analysis and the parametric step to test multiple values in one simulation.

The resistor values were modified to reflect change in bandwidth and capacitor values for the center frequency. Inductor was kept constant because high inductance will be large in size and expensive.

Initially, the resistor values 50Ω and 200Ω were tested to determine a range of values less than or larger than 100Ω for further simulations. Similarly, the capacitor values were tested for 20nF and 100nF. In second set of simulation, the resistor values 100Ω, 150Ω, and 200Ω were tested with 20nF capacitor for determining the a bandwidth closer to 50kHz. Finally, 160Ω was tested due to it being a common resistor value, readily available in the market, and closer to 150Ω.

Result

Table 2 represents the values of bandwidth and center frequency recorded from bode plots generated for the different capacitor, resistor, and inductor values.

Table 2: Bandwidth and center frequency values for various capacitors and resistors

Trial number	Capacitor(nF)	Resistor(Ω)	Inductor(μH)	Bandwidth (kHz)	Center Frequency (kHz)
1	56	50	33	56.71	120.45
2	56	100	33	28.35	117.93
3	56	200	33	14.18	117.29
4	20	50	33	158.78	211
5	100	50	33	31.76	89.04
6	20	100	33	79.39	199.89
7	20	150	33	52.93	197.7
8	20	200	33	39.69	196.9

Figure 4 is the bode plot for final test simulated for 160Ω resistor, 20nF capacitor and 33uH inductor. The recorded Bandwidth is 49.62kHz and center frequency 197.47kHz.

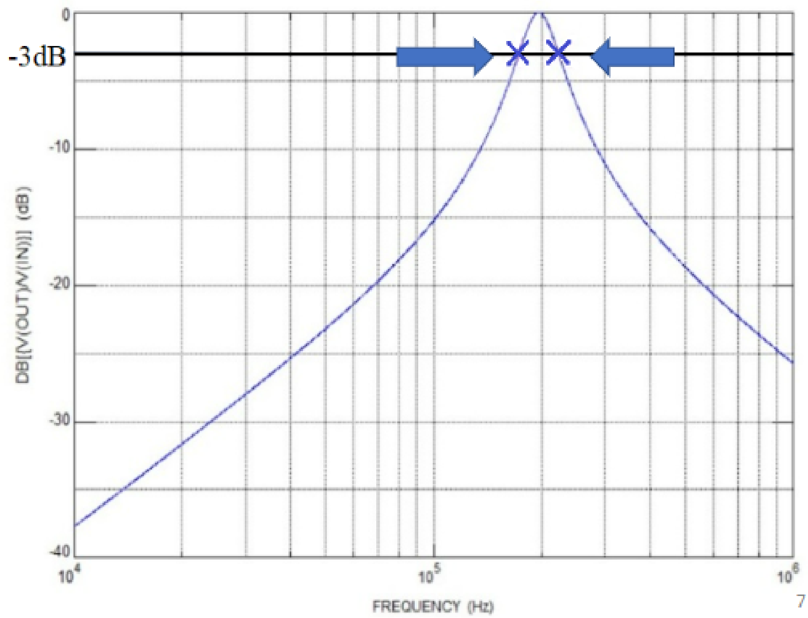

Figure 4: Bode plot for 160Ω resistor and 20nF capacicitor

Circuit Analysis and Discussion

In the final result shown in Figure 4, the minor cutoff frequency $f1$ equals $172.6618KHz$, and the larger cutoff frequency $f2$ equals $222.2798KHz$. The value of -3db bandwidth can be obtained by calculating the absolute difference value of $f1$ and $f2$, which equals $49.6179KHz$. The center frequency value obtained by dividing the sum of $f1$ and $f2$ by two equals $197.471KHz$, which is within the $\pm5\%$ marginal error range of $200KHz$ center frequency requirement.

Based on experimental results, it is clear that the value of -3db bandwidth decreases as the value of the resistor increases. The center frequency, on the other hand, only depends on the value of capacitor and inductor.

One intriguing fact the team found when calculating the center frequency value is that the result is different using two approaches. By substituting $L = 33u$ and $C = 20n$ into (5), the team obtained the theoretical center frequency value of $195.906KHz$, which is $1.5KHz$ below the actual center frequency. The possible explanation for such error is the precision of the simulation tool the team used does not reach a theoretical level. Moreover, random errors might occur when selecting a specific location on the graph using the cursor, which eventually leads to the difference of center frequency values. In any case, both actual and theoretical center frequency value are within the $\pm5\%$ marginal error range of $200KHz$, which means they are both acceptable.

Cost Estimation and Printed Circuit Board (PCB) design

From Digi key[3], which is an online electronic store, the components were chosen in terms of their unit price, quantity in stock, price for 15000 pieces, shipping cost. Table 3 breaks down the finalized parts with their Digi key number and manufacturer number for reference. Since more than 15000 were available in stock, the lead time is zero. The arrival time is said to be 1-2 business days and a shipping cost of $20.97

Table 3: Electronic parts details and price from Digi Key

Component	**Digi key part#**	**Manufacturer #**	**In stock Quantity**	**unit price (bulk)**	**Total price**
160Ω resistor	2019-CF1/4CT52R161JTR-ND	CF1/4CT52R161J	37487	$ 0.01078	$161.70
20nF capacitor	478-10428-2-ND	08051C203JAT4A	64528	$ 0.06026	$903.90
33uH inductor	CV201210-330KTR-ND	CV201210-330K	17390	$ 0.03478	$521.73

The 160Ω is a through hole type with 0.25W power rating and ±5% tolerance. The 20nF capacitor is surface mount with 100V voltage rating and ±5% tolerance. The 33uH inductor is a surface mount type that has 5mA current rating, 1.25Ω DC resistance, ±10% tolerance.

The software utilized to design the PCB was KiCad that helps to visualize the board in 3D and the connectivity between the parts. First, the bandpass filter was designed in the schematic window of KiCad[4]. The resistor, inductor, capacitor, and a voltage source were placed as shown in Figure 5. Digi Key part numbers of the elements were included as easy reference. The footprints were selected with respect to the details found in the datasheets in Digi Key.

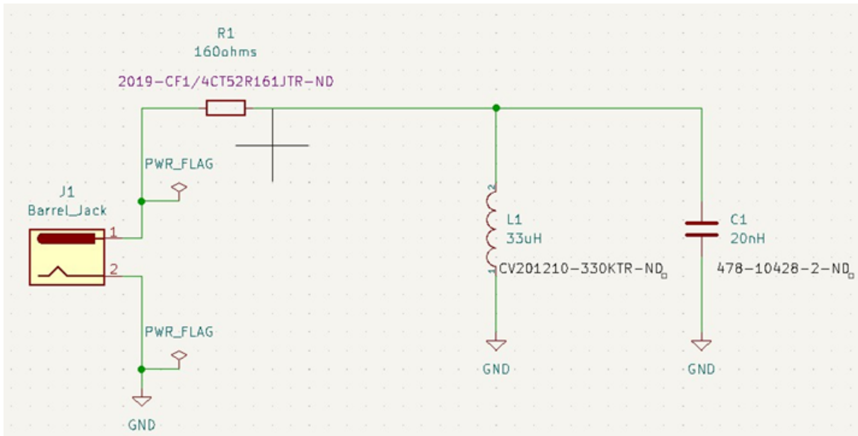

Figure 5: Band pass filter schematic in KiCad

Through the Netlist file format, the schematic was transformed into a PCB board. Figure 6 shows the final board design with their dimensions. The pads were traced in copper on the front layer of the board. While the front and back board were covered with copper. The dimensions are placed in the user drawing layer.

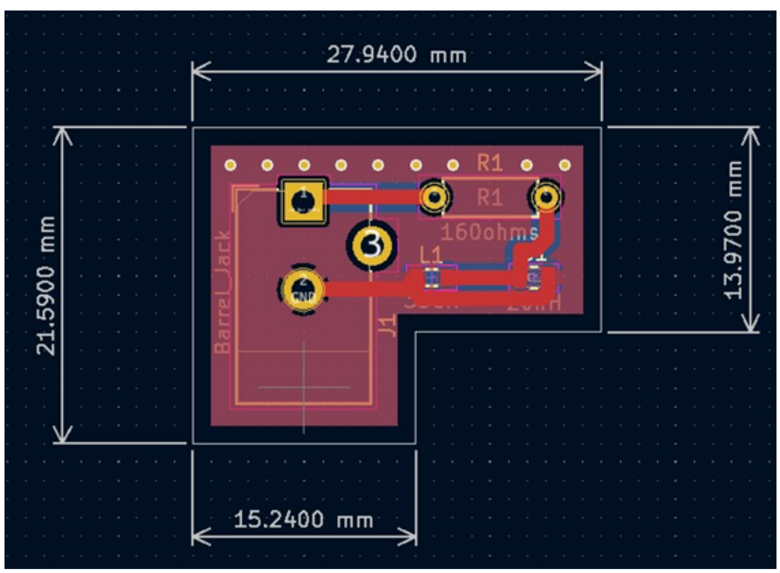

Figure 6: PCB board design in KiCad

The board was converted to Gerber file for cost estimation. Next, the PCB cost was obtained from JLCPCB[5], which is a company that produces PCB from the given design.. It consists of one layer, and the base material is Aluminum. The total cost to print 15000 boards is $450.80

and the shipping cost is \$20.19. The expected building time is four to five days, and the shipping will take 3-8 business days. The total cost for all the parts and PCBs, including shipping cost, for 15000 units is \$2079.29. The expected arrival time is at most two weeks.

Conclusion and Recommendation

The team was assigned to redesign a bandpass filter circuit by Acme company to meet the requirements of -3db bandwidth of 50KHz, and 200KHz of center frequency with ±5% tolerance. After running nine test cases using TopSpice while changing the value of resistor and capacitor, the team finalized the schematic with resistor value of 160Ω, inductor value of $33uH$, and capacitor value of $20nF$. The final design has center frequency value of $197.471KHz$ and -3dB bandwidth of $49.6179KHz$, which matches the requirement of 50kHz bandwidth and 200kHz center frequency. The electronic parts were chosen from Digi Key and PCB from JLCPCB. The final cost of 15000 units including shipping cost is \$2079.29, which is an acceptable price for this project.

The teams recommends using resistor with the value of 160Ω due to its low price. Moreover, 160Ω resistors have a huge number of stock on the market, which would significantly reduce the waiting period.

Reference

[1] TopSpice website. https://penzar.com/topspice/topspice.htm (accessed Feb 13, 2022).

[2] Dr. S. Ziaeefard, “BandPass Filter 1”, ECE 3090, Feb 2022.

[3] Digikey website. https://www.digikey.com/

[4] KiCad about website https://www.kicad.org/about/kicad/

[5] JLCPCB website https://jlcpcb.com/